J/Ψ suppression in nuclear collisions at SPS energies*

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Abstract

We have carried out a first calculation of J/Ψ production from nuclear collisions within the covariant transport approach HSD, which has been very successful in describing both hadronic and electromagnetic observables from heavy-ion collisions at intermediate and high energies. The production of J/Ψ's is based on the Lund string fragmentation model, while its interactions with hadrons are included by conventional cascade-type two-body collisions. Adopting 6 mb for the J/Ψ-baryon cross sections and 3 mb for the J/Ψ-meson cross sections above the $D\bar{D}$ threshold, we find that data on J/Ψ suppression from both proton-nucleus and nucleus-nucleus collisions (including Pb + Pb) can be explained without assuming the formation of a quark-gluon plasma in these collisions. Our microscopic studies thus confirm the suggestion of Gavin *et al.* that J/Ψ suppression observed in nuclear collisions is largely due to absorption by comovers, i.e., the produced mesons.

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Because of color screening a J/Ψ dissolves in a quark-gluon plasma. Matsui and Satz [1] thus proposed that a suppression of the J/Ψ yield in ultra-relativistic heavy-ion collisions is a plausible signature for the formation of the quark-gluon plasma in these collisions. This suggestion has stimulated a number of heavy-ion experiments at CERN SPS to measure the J/Ψ production via its dimuon decay. Indeed, these experiments have shown a significant reduction of the J/Ψ yield when going from proton-nucleus to nucleus-nucleus collisions [2, 3]. Especially for Pb + Pb at 160 GeV/u an even more dramatic reduction of J/Ψ has been reported by the NA50 collaboration [4].

To understand the experimental results, models based on J/Ψ absorption by hadrons have also been proposed. In Ref. [5], Gerschel and Hüfner have shown that the observed suppression of J/Ψ in nuclear collisions is consistent with the hadronic absorption scenario if one assumes that the J/Ψ-nucleon absorption cross section is about 6-7 mb. On the other hand, Gavin *et al.* [6], based also on the hadronic absorption model, have found that although J/Ψ absorption by nucleons is sufficient to explain the proton-nucleus data, it can not account for the suppression seen in nucleus-nucleus collisions. Introducing J/Ψ absorption by the produced mesons, which they call the 'comovers', with a cross section of about 3 mb, they can also obtain a satisfactory account of the nucleus-nucleus data. They attribute the difference between their conclusion and that of Ref. [5] to the different consideration in the thickness of nuclear matter where the produced J/Ψ has to pass through. In both studies, the dynamics of the collisions is based on the Glauber model, so a detailed space and time evolution of the colliding system is not included. In particular, the transverse expansion of the system is ignored in these studies. Especially for nucleus-nucleus collisions involving heavier beams, such as the recent Pb+Pb collisions at 160 GeV/nucleon, the dynamics is more complex than in proton and S induced reactions. Although the hadronic absorption model of Ref. [6] has been shown to also explain the data [7], an improved study based on a more realistic dynamic model will be very useful in clarifying the underlying assumptions.

In this work we will carry out a study of J/Ψ production and suppression at SPS energies using the covariant transport approach HSD [8]. This nonequilibrium model has been shown to describe satisfactorily both the measured hadronic observables (rapidity distributions, transverse momentum spectra etc. [8]), which are sensitive to the

final stage collision dynamics, and dilepton spectra [9, 10, 11], which reflect also the initial hot dense stage of the collisions. It thus gives a more realistic description of the heavy-ion reaction dynamics than those used in Refs. [5, 6, 7]. Within this approach we can check if the simple hadronic absorption model used in both Ref. [5] and Refs. [6, 7] can indeed explain quantitatively the observed J/Ψ suppression. Furthermore, we can check if the J/Ψ is destroyed by nucleons before mesons are produced, since this assumption has been used in Ref. [12] to argue that J/Ψ absorption by mesons should be neglected, and the large suppression observed in Pb+Pb collisions might partly be due to the quark-gluon plasma. We will not address the question of whether the magnitude of the J/Ψ-hadron cross sections used is correct or can be justified by nonperturbative QCD. According to Ref. [13], these cross sections might be negligibly small in hadronic matter due to the small size of the J/Ψ and its large mass gap from open charms. However, it might well be true that the $c\bar{c}$ pair is first produced in a color-octet state together with a gluon and that this more extended configuration has a larger interaction cross section with baryons and mesons (i.e., 6 mb and 3 mb, respectively) before the J/Ψ singlet state finally emerges.

In HSD a J/Ψ (or better $c\bar{c}$ pair) is produced from string fragmentation [14] in the initial stage of a nuclear collision. Since the probability of producing a J/Ψ is very small, a perturbative approach is used in our study: i.e., whenever an $s\bar{s}$ pair (Φ-meson) is produced in the string decay, a J/Ψ is produced with a probability factor W, which is given by the ratio of the J/Ψ to Φ cross section at a center-of-mass energy $\sqrt{s}$ of the baryon-baryon collision, i.e.,

$$W = \frac{\sigma_{BB\to J/\Psi+X}(\sqrt{s})}{\sigma_{BB\to \Phi+X}(\sqrt{s})}. \tag{1}$$

We then follow the motion of the J/Ψ in hadronic matter throughout the collision dynamics by treating its collisions with hadrons in the same way as for other hadron-hadron collisions [8]. We use as in Refs. [6, 7] 6 mb for J/Ψ-baryon collisions ($J/\Psi + B \to \Lambda_c + \bar{D}$) and 3 mb for J/Ψ-meson collisions ($J/\Psi + m \to D\bar{D}$) once the energies are above the threshold for these reactions. Since the J/Ψ production is treated perturbatively, light hadrons are not affected by these collisions in their propagation, however, the J/Ψ is destroyed.

Since in experiment the J/Ψ is measured in nuclear collisions from its decay into

dimuons, we calculate explicitly the dimuon invariant mass spectra from the collisions. This includes not only the decay of the J/Ψ but also the decay of other vector mesons (ρ, ω, and ϕ) as well as the Dalitz decay of π, η, ω, etc. Details on calculating the dilepton spectra from heavy-ion collisions up to invariant masses of about 1.5 GeV can be found in Refs. [9, 10]. Since both the Drell-Yan and open charm contributions are important for dileptons with invariant masses above 1.5 GeV, the latter being known e.g. for p + W reactions [15], we have simulated their yield by a background term which is fitted to the dimuon yield for p + W at 200 GeV/u.

We have carried out calculations for p+W, S + W and Pb + Pb collisions at 200 GeV/u as well as Pb+Pb collisions at 160 GeV/nucleon. All results presented below are obtained at an impact parameter of 2 fm. In Fig. 1 we show the dilepton invariant mass spectra for the three reactions normalized to the number of charged particles in the pseudorapidity bin $3.7 \leq \eta \leq 5.2$ and compare them with the experimental data from Ref. [16]. Since there are no data from the HELIOS-3 collaboration for Pb+Pb at 200 GeV/u, the S+W data at 200 GeV/u are employed for the comparison with the calculated results for Pb+Pb. It is seen from Fig. 1 that in the p+W and S+W cases the theoretical results agree well with the data on an absolute scale which implies that apart from the low mass dimuon spectrum - which has been analysed in Ref. [10] - also the J/Ψ region is described reasonably well. For S+W in the invariant mass range from 1.3 GeV $\leq$ m $\leq$ 2.5 GeV we miss about a factor of 2 in the dilepton yield, which might be due to the contribution from $\pi a_1 \rightarrow \mu^+\mu^-$ [17] and/or an enhancement of open charm channels in the nucleus-nucleus case; these channels are not included in the present transport approach and require further analysis. When comparing the theoretical spectrum for Pb+Pb with the data for S+W in the J/Ψ mass region (Fig. 1c), we find a drastic suppression as compared to the S + W reaction. We, therefore, may already conclude that the simple calculations of Refs. [6, 7] are quite reasonable and the observed large suppression of J/Ψ production in nuclear collisions (especially Pb + Pb) can be accounted for by hadronic absorption.

To understand more clearly the J/Ψ absorption in hadronic matter, we show in Fig. 2 the time evolution of the J/Ψ abundance for p + W and S + W at 200 GeV/u as well as for Pb + Pb at 160 GeV/u. The solid curves show results with absorption

by both baryons and mesons while the dashed curves only reflect the absorption by baryons. The dotted lines show the actual number of J/Ψ's in the simulation without including any reabsorption. We see that J/Ψ absorption by mesons is important in both S+W and Pb+Pb collisions as suggested in Refs. [6, 7]; this is in contradiction to the assumptions of Ref. [12]. On the other hand, there is no sizeable effect from J/Ψ-meson collisions for p+W due to the low meson densities involved. The enhancement of J/Ψ suppression in Pb + Pb collisions compared to S + W reactions is basically due to a longer reaction time with comovers as seen from Fig. 2b) and c).

For Pb+Pb collisions, the propagation length L of the J/Ψ in nuclear matter estimated by the Glauber theory is found to saturate with impact parameter b $\leq$ 9 fm [4, 18], i.e., L $\approx$ 10.5 - 11.5 fm. Thus when plotting the J/Ψ suppression factor versus L, a sudden and dramatic reduction is found experimentally [4]. As argued by Gavin and Vogt [6], this reduction is an artefact of the representation and should become smooth as a function of the transverse energy produced which increases drastically with decreasing impact parameter. We have investigated the latter question in more detail and show in Fig. 3 the calculated J/Ψ suppression factor for Pb + Pb at 160 GeV/u as a function of the transverse energy produced normalized to the transverse energy E_T^{max} for b = 0 fm. The corresponding values for the impact parameter are in steps of 1 fm starting from b = 11 fm to b = 1 fm. Indeed, as in the analysis by Gavin and Vogt [7] the J/Ψ suppression is found to be smooth in the transverse energy and approximately agrees with the preliminary data from [4].

In order to explore if the energy density in these reactions might be large enough to create a quark-gluon plasma in some region of space and time, we show as a function of time (Fig. 4) the volume with energy density above 2, 3, and 4 GeV/fm^3 for S + W at 200 GeV/u and Pb + Pb at 160 GeV/u for a reaction at b = 2 fm. We do not show the result for p+W at 200 GeV because the corresponding volumes are zero in the latter case. In these calculations the energy density is computed as

$$E(x) = (\Delta V(x)\gamma(x))^{-1}\{\sum_{baryons\ i\ \epsilon\ \Delta V} \sqrt{p_i^2 + m_i^2} + \sum_{mesons\ j\ \epsilon\ \Delta V} \sqrt{p_j^2 + m_j^2}\}, \qquad (2)$$

where all mesons, but only baryons that have scattered at least once, have been counted. In eq. (2), $\gamma(x)$ is the Lorentz-factor associated with the cell $\Delta V(x)$, which is taken to

be 1 fm^3([1]), in the nucleus-nucleus center of mass.

It is seen that in Pb+Pb collisions there is an appreciable volume of high energy density above 3 GeV/fm^3 ($\approx$ 300 fm^3) for time scales of a few fm/c, where a quark-gluon plasma (QGP) might be formed in the reaction[2]. This region of high energy density is about 20 % of the volume of Pb and - from our point of view - should not be adequately described by a hadronic transport theory. The actual volume of high energy density (above 3 GeV/fm^3) for S + W is only about 50 fm^3, but the volume per participating projectile nucleon is roughly the same. Thus central S + W and Pb + Pb collisions should show similar features when normalizing by the number of charged particles in a more forward rapidity bin. As an example we mention the normalized dimuon spectra (within the HELIOS-3 acceptance) for the two reactions in Fig. 1b) and 1c), which within 10 - 20 % are practically the same for invariant masses below 2 GeV.

Since in p+W collisions mesons do not contribute substantially to J/Ψ absorption and the energy density is not high either, the fact that the theoretical results agree with the data can be used to justify the use of 6 mb for the J/Ψ-baryon cross sections. Furthermore, the agreement between the theoretical results with the S+W data, where quark-gluon plasma effects should be of minor importance, indicates that the 3 mb used for the J/Ψ-meson cross sections is also reasonable.

We note, furthermore, that our analysis yields a maximum suppression of J/Ψ's at high baryon and meson density, which also directly correlates with a high energy density. Thus alternative assumptions about J/Ψ suppression, that rise almost linearly with the energy density, cannot be ruled out at the present stage.

In conclusion, we have carried out a first microscopic transport study of J/Ψ production and absorption in nuclear collisions. Including only absorption by hadrons, we confirm the results of Refs. [6, 7] based on a simple Glauber model that the observed suppression in both proton-nucleus and nucleus-nucleus collisions can be explained. In particular, the absorption of J/Ψ's by produced mesons is important in nucleus-nucleus collisions and especially for Pb + Pb, where the J/Ψ-hadron reactions extend

[1] The results in Fig. 4 are independent of the cell size $\Delta V(x)$ from 0.15 to 1.5 fm^3.

[2] The critical energy density for a phase transition to the QGP is not accurately known; the value of 3 GeV/fm^3 is chosen for convenience.

to much larger times as compared to the S + W reaction. The scaling of the $c\bar{c}$ pair suppression with the geometrical path L according to Glauber theory is found to be misleading, since the dependence on the meson density, and thus on the transverse energy produced, is smooth.

Since the hadronic J/Ψ reabsorption is proportional to the hadron density and thus also approximately proportional to the energy density, we presently cannot rule out a possible dissociation of the $c\bar{c}$ pair within local QGP droplets, which are expected to be formed at least for energy densities above 3 GeV/fm^3. It might also happen that the $c\bar{c}$ pairs have a finite probability to escape from the QGP-phase; such a scenario would be hard to distinguish experimentally from the hadronic reabsorption model. At the present stage we can only exclude a full J/Ψ dissociation in the QGP-phase, if the critical energy density for the phase transition is below about 1.5 GeV/fm^3, because the suppression factors calculated for S + W at 200 GeV/u and Pb + Pb at 160 GeV/u are then larger than those seen experimentally so far. In order to discriminate between the different model assumptions we need better information on the $c\bar{c}$ cross sections with hadrons; a task we here have to delay for future work.

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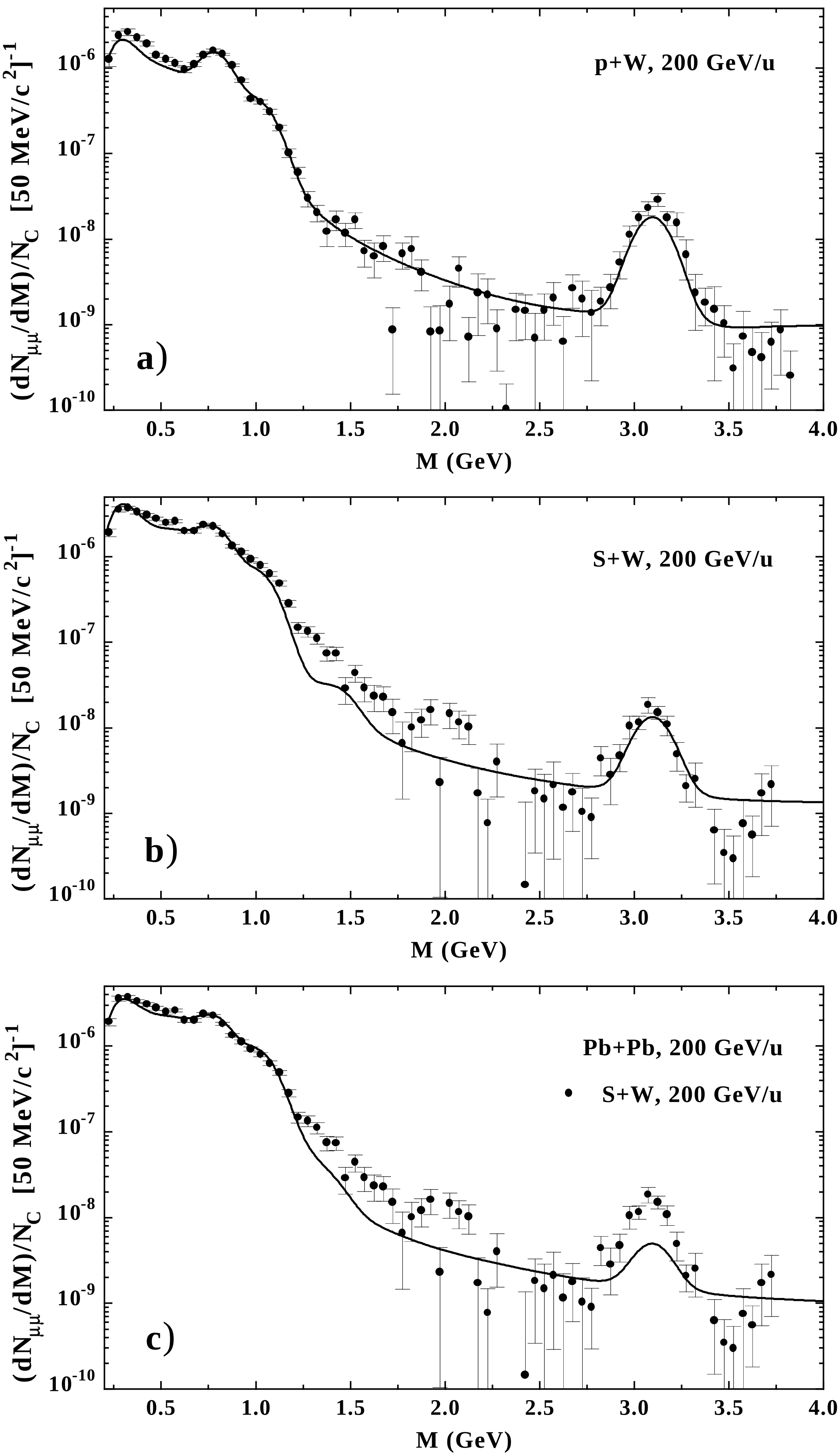
Figure Captions

Fig. 1: Dimuon invariant mass spectra from p+W, S+W, and Pb+Pb collisions at 200 GeV/nucleon in comparison to the data of the HELIOS-3 collaboration [16]. For the case of Pb + Pb (c) we compare to the data for S+W since no equivalent experimental spectra are available.

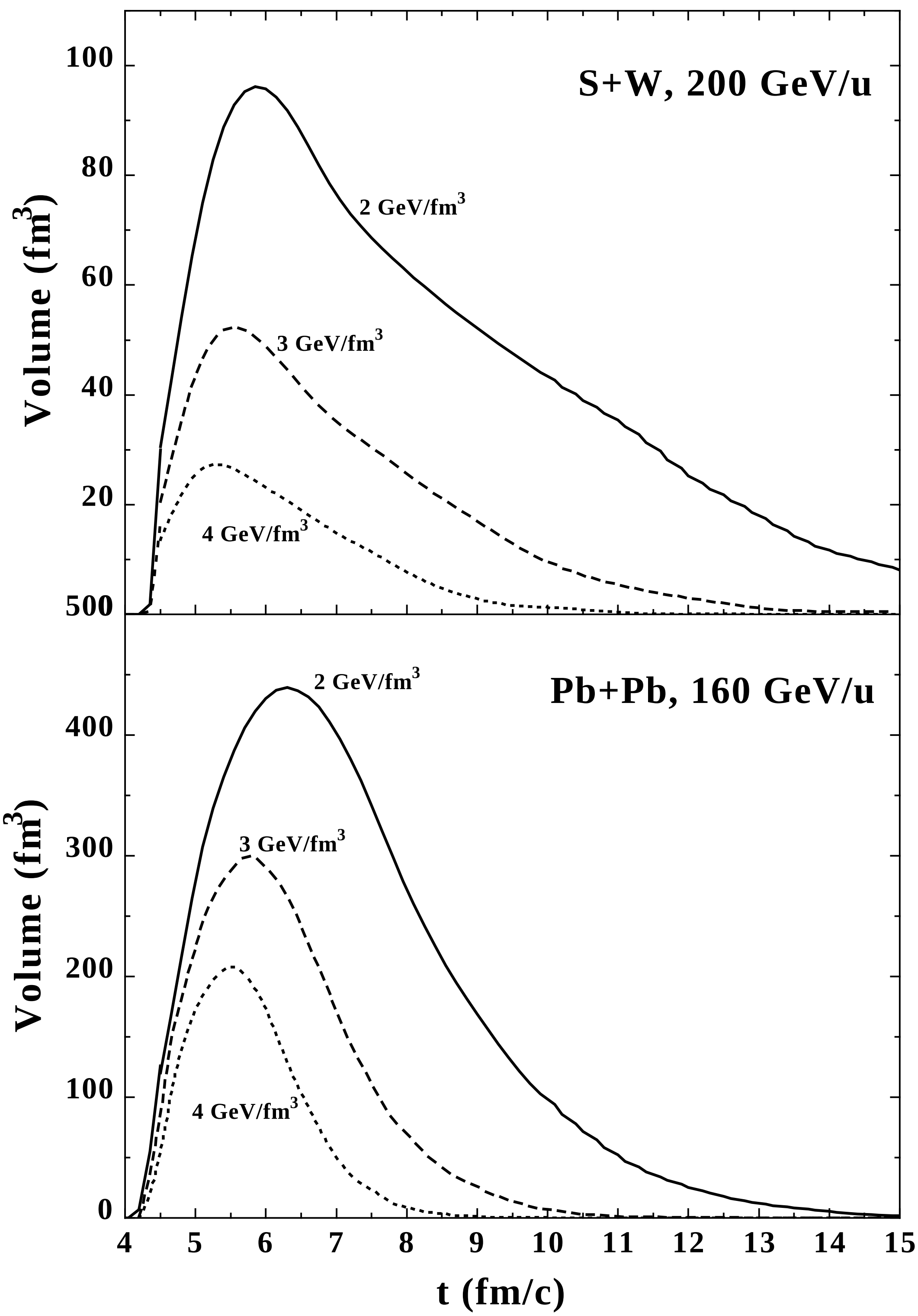
Fig. 2: Time dependence of the J/Ψ abundance for p+W, S+W at 200 GeV/u and Pb+Pb collisions at 160 GeV/u. The dotted lines show the total number of produced J/Ψ's without reabsorption; the dashed lines display the J/Ψ number when including absorption by baryons while the full lines show the results of our calculation when including absorption by both baryons and mesons as described in the text. The J/Ψ number calculated is proportional to the actual multiplicity for S + W and Pb + Pb, whereas the statistics have been increased for p + W by a factor 100.

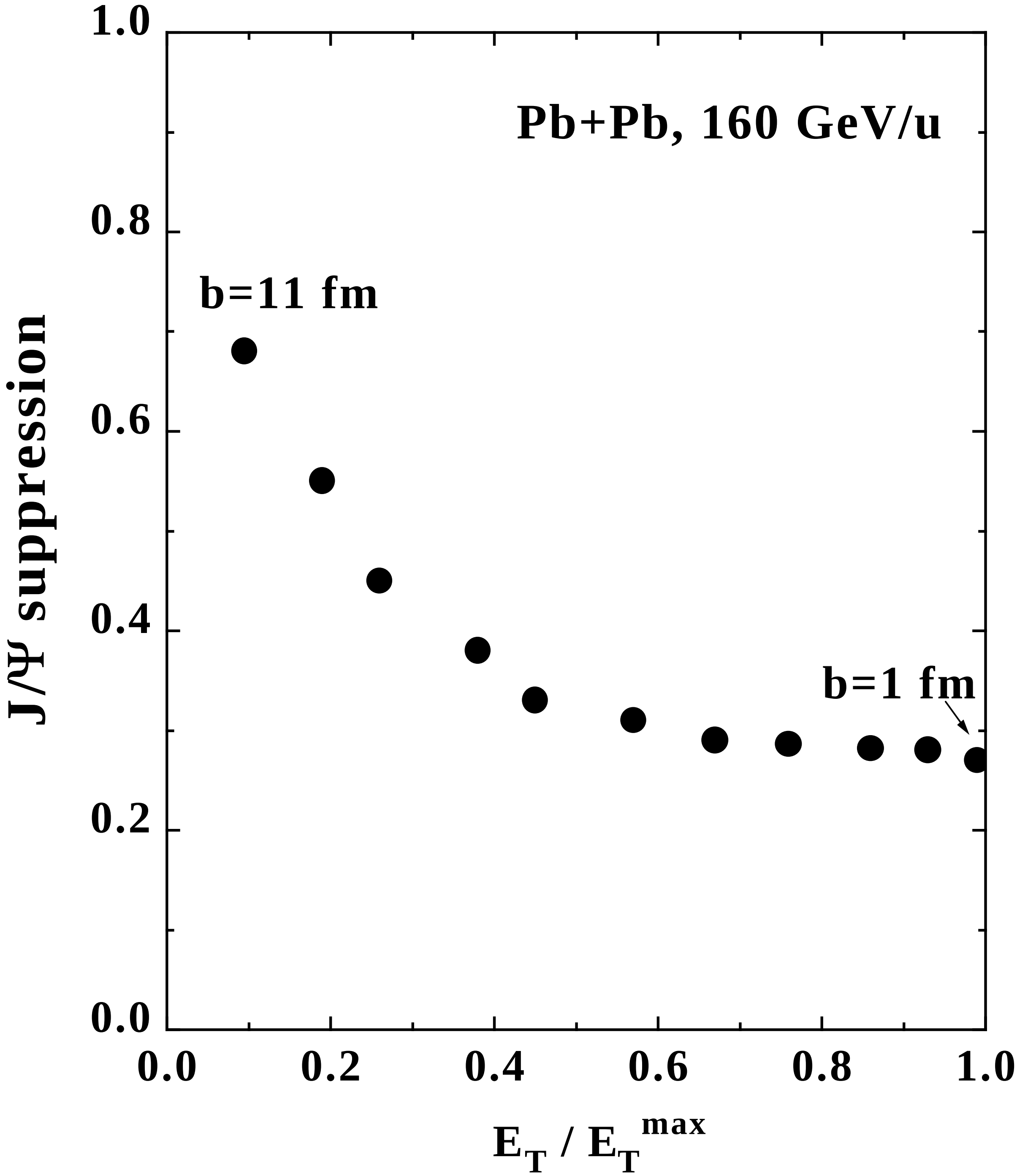
Fig. 3: The J/Ψ suppression factor for Pb + Pb at 160 GeV/u as a function of the transverse energy normalized to the maximum transverse energy E_T^{max} at b = 0 fm. The individual dots stand for a fixed impact parameter b which decreases in steps of 1 fm from 11 fm to 1 fm.

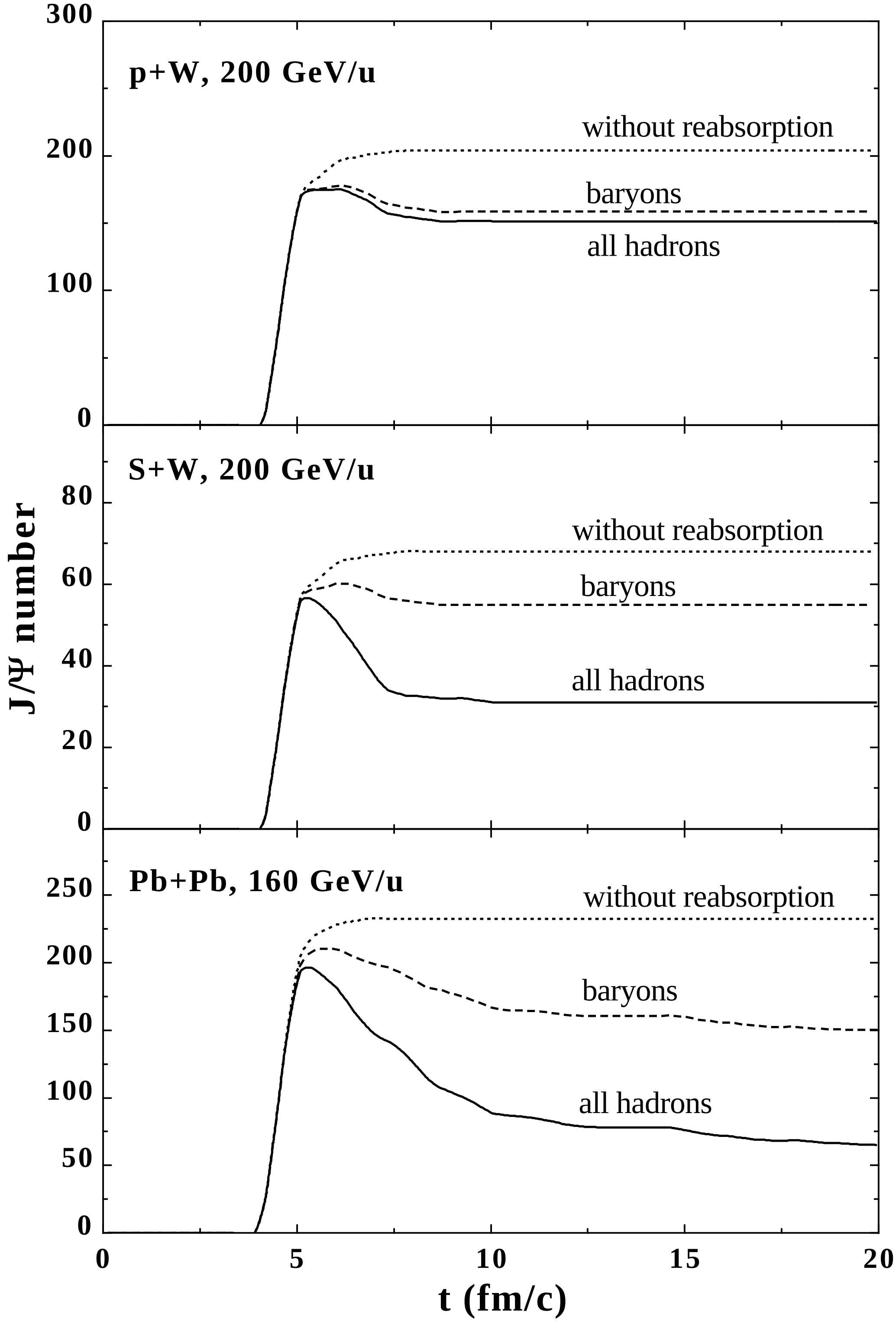
Fig. 4: Time evolution of the reaction volume with an energy density above 2, 3, and 4 GeV/fm^3 for S+W at 200 GeV/u and Pb + Pb at 160 GeV/u.



p+W, 200 GeV/u
a)
S+W, 200 GeV/u
b)
Pb+Pb, 200 GeV/u
S+W, 200 GeV/u
c)
(dN$_{\mu\mu}$/dM)/N$_C$ [50 MeV/c^2]$^{-1}$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
M (GeV)


S+W, 200 GeV/u
2 GeV/fm3
3 GeV/fm3
4 GeV/fm3
Volume (fm3)
100
80
60
40
20
500
Pb+Pb, 160 GeV/u
2 GeV/fm3
3 GeV/fm3
4 GeV/fm3
Volume (fm3)
400
300
200
100
0
4
5
6
7
8
9
10
11
12
13
14
15
t (fm/c)


Pb+Pb, 160 GeV/u
b=11 fm
b=1 fm
J/Ψ suppression
E_T / E_T^max
0.0
0.2
0.4
0.6
0.8
1.0


p+W, 200 GeV/u
without reabsorption
baryons
all hadrons
S+W, 200 GeV/u
without reabsorption
baryons
all hadrons
Pb+Pb, 160 GeV/u
without reabsorption
baryons
all hadrons
J/Ψ number
t (fm/c)
0
5
10
15
20
300
200
100
0
80
60
40
20
0
250
200
150
100
50
0